STATISTICS
TEXAS A&M UNIVERSITY

Course Introduction and Background on Surveys and Time Domain Astronomy

September 14, 2016

Course Information

What is Astrostatistics?

Time Domain Astronomy Background

Surveys

Outline

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Tentative Schedule

Date	Topic
Sept 7	Introduction, Time Domain Astronomy (James Long)
Sept 14	Time Domain Astronomy (James Long)
Sept 21	Time Domain Astronomy (James Long)
Sept 28	Bootstrap, Hypothesis Testing (Jogesh Babu)
Oct 5	Bootstrap, Hypothesis Testing (Jogesh Babu)
Oct 12	Spectral Data, Bayesian SED Fitting (Viviana Acquaviva)
Oct 19	Something Bayesian (Tom Loredo)
Oct 26	Approximate Bayesian Computation (Jessi Cisewski)
Nov 2	Spectral Data, Approximate Models (James Long)
Nov 9	Spectral Data, Approximate Models (James Long)
Nov 16	Student Presentations
Nov 23	NO CLASS
Nov 30	Student Presentations

Where to Find Course Information

- course website: `http://stat.tamu.edu/~jlong/astrostat`
- email me: `jlong` + at + `stat.tamu.edu`
- office hours: after class or by appointment
- course lectures: videos on samsi website

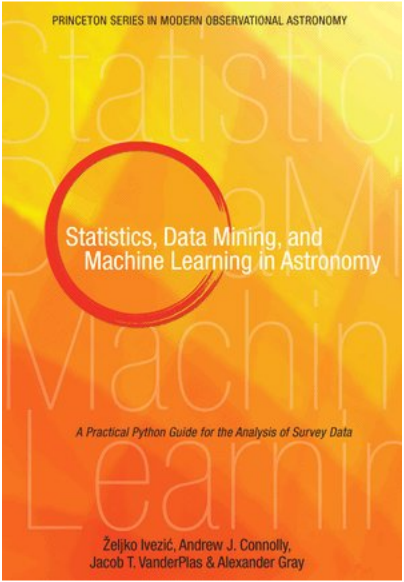
Grading / Work Load

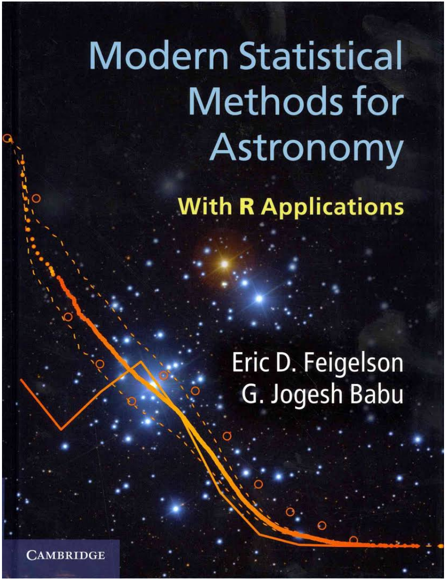
- P/F for everyone
- sign up sheet in back of classroom
- no homework
- suggested readings on course website
- target audience: 1st year statistics PhD student
- course project
  - choose topic by mid October, submit 1 paragraph description
  - meet with me in early November to discuss progress
  - $\approx$ 30 min in class presentations on Nov 16,30
  - more details at later lectures

Project Topic Suggestions

- reproduce article results / apply to new data set
  - "Unsupervised Transient Light Curve Analysis Via Hierarchical Bayesian Inference" by Sanders, ApJ
  - "Modeling lightcurves for improved classification . . ." by Faraway, Statistical Analysis and Data Mining
  - "Some Aspects of Measurement Error . . . " Kelly ApJ
  - "A flexible method of estimating luminosity functions" Kelly ApJ
- tutorial on research / coding tools
  - bayesian computing, eg stan
  - ipython / jupyter notebooks
- simulation study, algorithm comparison
- overview of topic in astronomy we did not cover**
  - photometric redshift estimation
  - source extraction from images
  - statistics of gravity waves

Astrostatistics Textbooks





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Common Themes

- complex, multi–stage inference problems
  - “A framework for statistical inference in astrophysics” [4]
- measurement error, heteroskedastic errors with known variance
- large data sets
- data types: images, spectra, maps
- complex scientific questions that require close astronomer–statistician collaboration

Statistical Methods Used: Pretty Much Everything

- machine learning
- measurement error models
- samplers, MCMC
- functional data analysis
- time series
- hierarchical models
- spatial statistics

Getting Involved in Astrostat Research @ SAMSI

WG 1: Uncertainty Quantification and Astrophysical Emulation

Leaders: Derek Bingham (SFU) and Earl Lawrence (LANL)
To join email: wg1@sakai.duke.edu

WG 2: Synoptic Time Domain Surveys

Leaders: Ashish Mahabal (Caltech) and G. Jogesh Babu (PSU)
To join email: wg2@sakai.duke.edu
Weekly meeting time: Tuesdays at 12:00-1:00PM, EDT

WG 3: Multivariate and Irregularly Sampled Time Series (MISTS)

Leaders: Ben Farr (U.Chicago) and Soumen Lahiri (NCSU)
To join email: wg3@sakai.duke.edu

WG 4: Astrophysical Populations (AP)

Leaders: Jessi Cisewski (Yale) and Eric Ford (PSU)
To join email: wg4@sakai.duke.edu
Weekly meeting time: Thursdays at 12:00-1:00PM, EDT

WG 5: Statistics, Computation, and Modeling in Cosmology (COSMO)

WG Leaders: Jeff Jewell (JPL) and Joe Guinness (NCSU)
To join email: wg5@sakai.duke.edu

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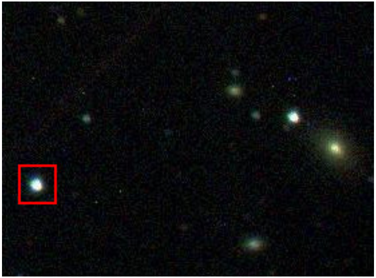
Telescopes Take Images of the Night Sky

Images to Catalogs

For every object in every image, need to identify and characterize objects:

- location (RA/Dec)
- brightness (magnitudes)
- filter (or band)
- time (MJD)

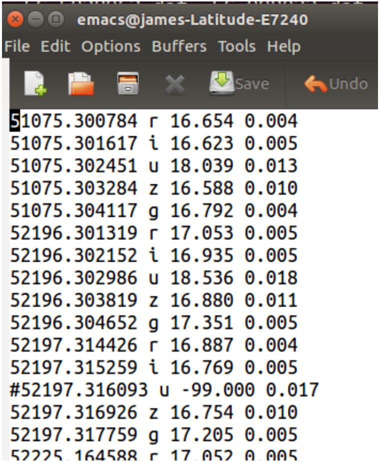


Hard task (possible project):

- "SExtractor: Software for source extraction" Aanda, Bertin [1]
- "The SDSS Imaging Pipeline" Lupton [2]
- "Celeste: Variational inference for a generative model of astronomical images" ICML, Regier [3]

Time Domain: Objects are Observed Over Time

When telescope takes repeated images of the same area of the sky, we obtain many brightness measurements for each object.

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52196.301319 r 17.053 0.005
52196.302152 i 16.935 0.005
52196.302986 u 18.536 0.018
52196.303819 z 16.880 0.011
52196.304652 g 17.351 0.005
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#52197.316093 u -99.000 0.017
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52197.317759 g 17.205 0.005
52225.164588 r 17.052 0.005
```

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Surveys

Surveys:

- Non–survey: Hey, there's something interesting over there, let's point our telescope at it.
- Survey: Observations are scheduled in advance with some science goals in mind.

Tradeoffs in Surveys:

- narrow vs wide
- shallow vs deep
- number of filters
- temporal coverage

Given a certain budget of telescope time, these are optimized for one (or several) science goals.

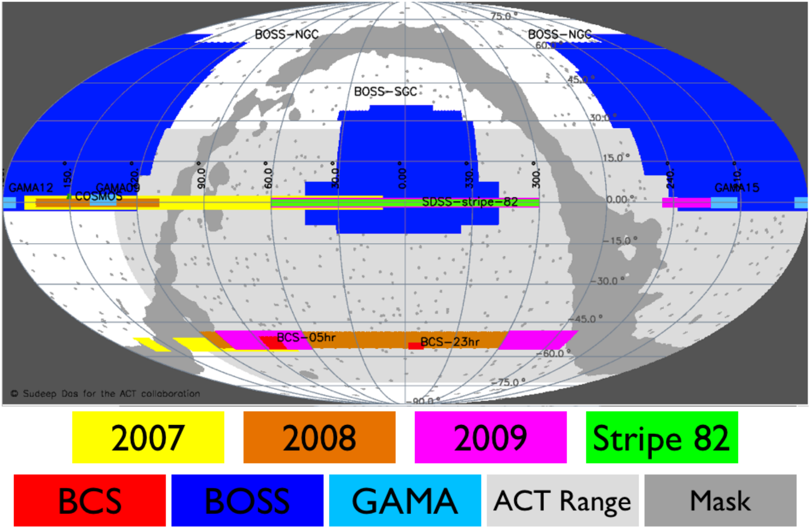
Tom Loredo's Talk on Surveys:

`https://www.samsi.info/wp-content/uploads/2016/08/Tutorial-CosmicDemographics_Loredo.pdf`

Major Time Domain Optical Surveys

- Sloan Digital Sky Survey – Stripe 82 (SDSS)
- Optical Gravitational Lensing Experiment (OGLE)
- Kepler
- Dark Energy Survey (DES)
- Large Synoptic Survey Telescope (LSST)

SDSS – Stripe 82

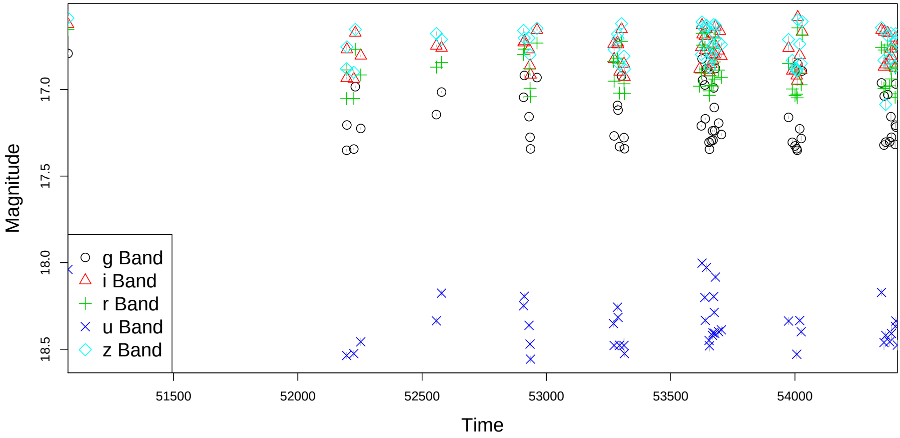


See Sesar [6] and Sesar [5]
Image credit: `https://inspirehep.net/record/859503/files/F3.png`

SDSS Photometry

- standard star catalog ($\approx$ 1 million): http://www.astro.washington.edu/users/ivezic/sdss/catalogs/stripe82.html
- variable source catalog ($\approx$ 67,000): http://www.astro.washington.edu/users/ivezic/sdss/catalogs/S82variables.html

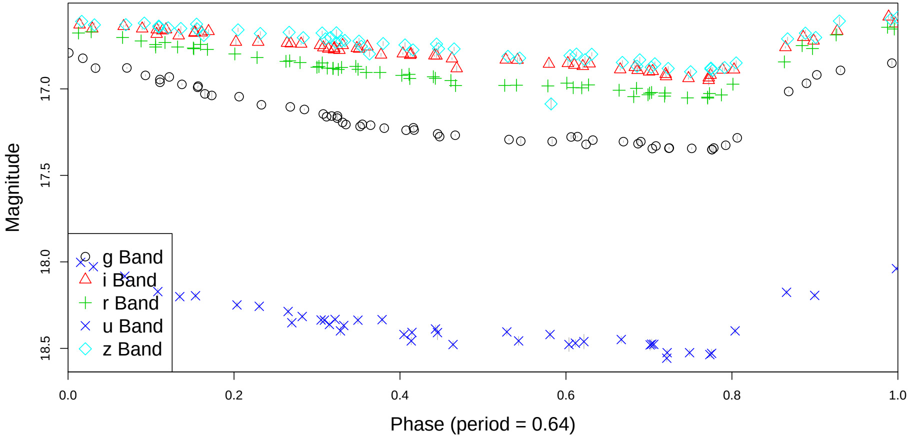
SDSS Variable Light Curve



- ≈ 67,000 of these in SDSS Stripe 82
- ≈ 70 observations / filter in 5 (u,g,r,i,z) filters
- ≈ 10 years

Folded Light Curve

Estimate period of 0.64 days, plot magnitude versus phase for object.



RR Lyrae variable star, useful for determining distance.

Selecting Variable Sources

- Data for single star is

$$D = \{(t_{jb}, m_{jb}, \sigma_{jb})\}_{j=1}^{n_b}$$

for $b = 1, \ldots, B$. Observe brightness m_{jb} at time t_{jb} with uncertainty σ_{jb} in filter (band) b.
- If a star is constant then a possible model is

$$m_{jb} = \mu_b + \epsilon_{jb}$$

where $\epsilon_{jb} \sim N(0, \sigma_{jb}^2)$.
- $\widehat{\mu}_b = (\sum \sigma_{jb}^{-2})^{-1} \sum_{j=1}^{n_b} \frac{m_{jb}}{\sigma_{jb}^2}$

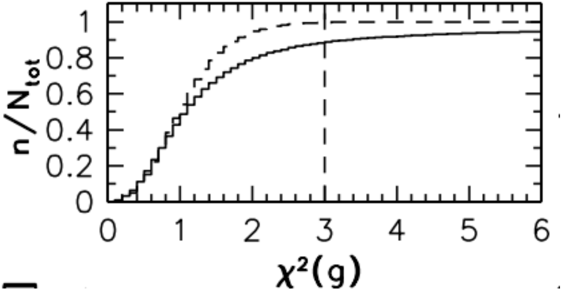
$$RSS(b) = \sum_{i=1}^{n_b} \left(\frac{m_{jb} - \widehat{\mu}_b}{\sigma_{jb}} \right)^2$$

- Large RSS(b) suggest variable.

Using RSS to Make Cuts

For example Sesar 2007 [6] defines

$$\chi^2(g) = \frac{1}{n_g - 1} RSS(g)$$



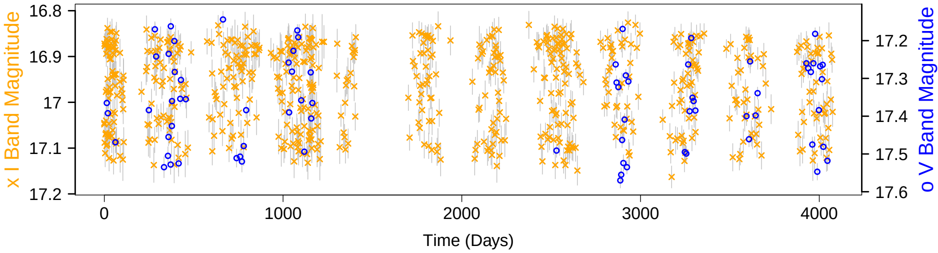
A source must have $\chi^2(g)$ above 3 to be labeled variable.

Optical Gravitational Lensing Experiment (OGLE)

Surveyed Small Magellanic Cloud, Large Magellanic Cloud, and Galactic Bulge.

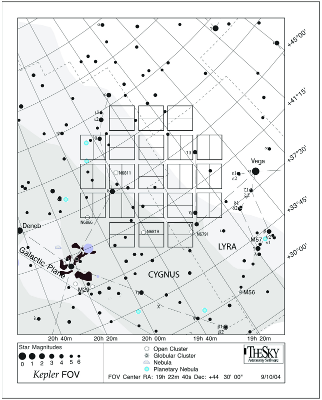
OGLE Photometry

- OGLE–III catalog of variables
  `http://ogledb.astrouw.edu.pl/~ogle/CVS/`
- ≈ 400,000 variable stars
- 2 filters (I,V)
- more data in I



Goal: Find transiting extrasolar planets.

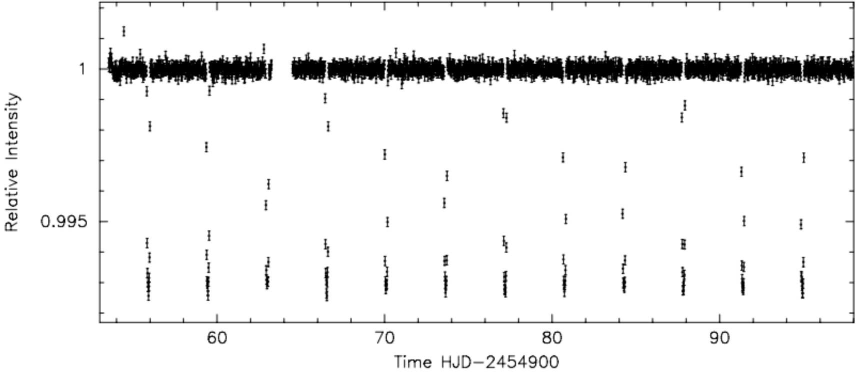
- observation every 30 minutes
- one filter
- $\approx 145,000$ main sequence stars



Transiting Method for Detecting Exoplanets:
`http://kepler.nasa.gov/multimedia/Interactives/HowKeplerDiscoversPlanetsElementary/flash.cfm`

Credit for Images: `https://en.wikipedia.org/wiki/Kepler_(spacecraft)`

Kepler Photometry



Planet transits every ≈ 3.5 days.

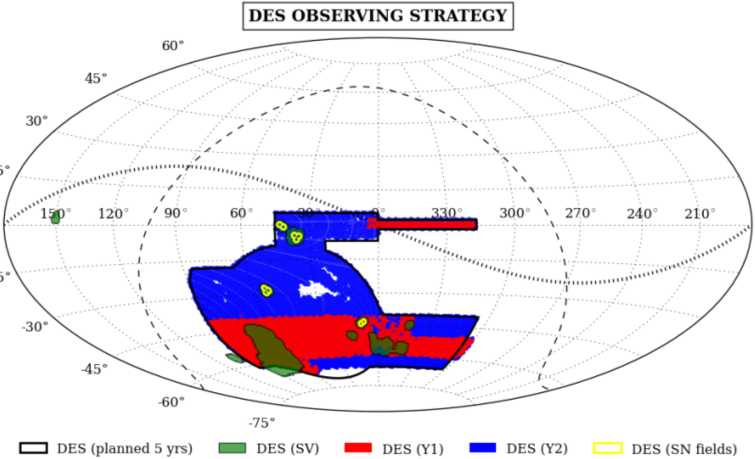
Dark Energy Survey

Goal: Investigate Large Scale Structure of Universe using

- Type Ia supernovae
- Baryon Acoustic Oscillations (BAO)
- Number of galaxy clusters
- Weak gravitational lensing

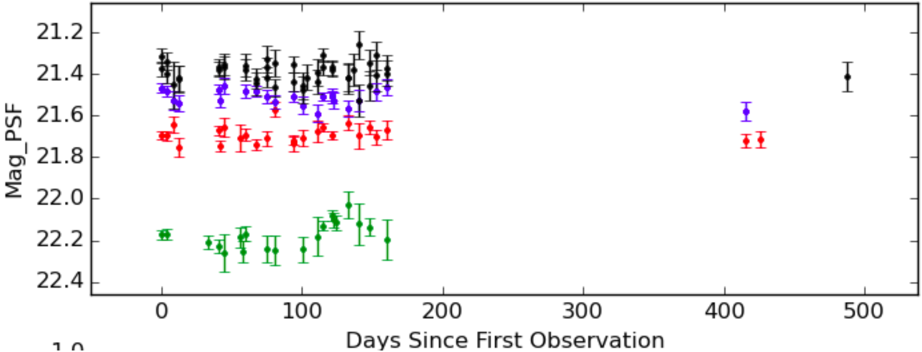
What is a good observing strategy for supernovae?

Dark Energy Survey Sky Coverage



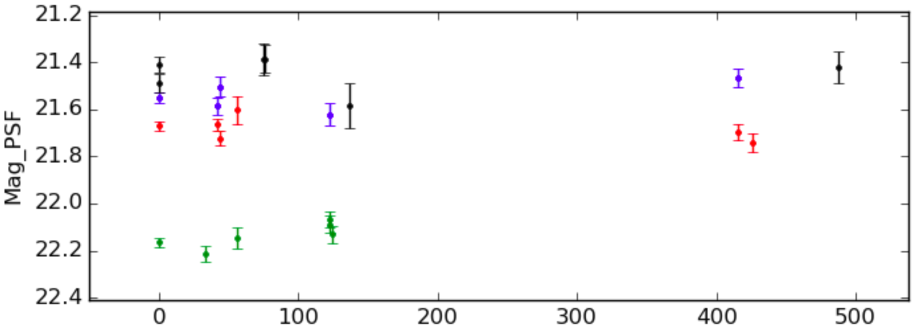
Taken from: `https://www.darkenergysurvey.org/the-des-project/survey-and-operations/`

Dark Energy Survey – Supernovae Fields Y1



Many observations / object but fewer objects.

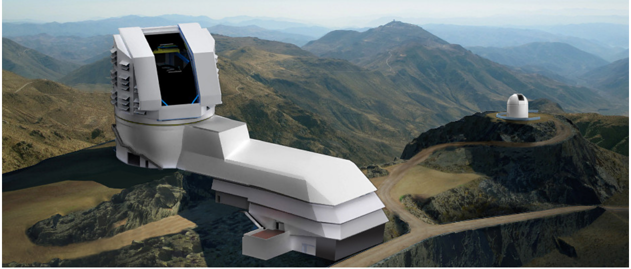
Dark Energy Survey – Wide Fields Y1



Few observations / object but many objects (≈ 100 million stars).

Large Synoptic Survey Telescope

- first light in 2019
- wide range of science goals
- unprecedented quantity of data



Summary

- large (and growing) amount of data
- different survey strategies to target different science goals
- data types: two modes of thinking
  - (vector valued) irregularly sampled **time series**
  - (vector valued) irregularly sampled **functional data**
- heteroskedastic magnitude error, "known" variance

Bibliography I

[1] Emmanuel Bertin and Stephane Arnouts. Sextractor: Software for source extraction. *Astronomy and Astrophysics Supplement Series*, 117(2):393–404, 1996.

[2] Robert Lupton, James E Gunn, Zeljko Ivezic, Gillian R Knapp, Stephen Kent, and Naoki Yasuda. The sdss imaging pipelines. *arXiv preprint astro-ph/0101420*, 2001.

[3] Jeffrey Regier, Andrew Miller, Jon McAuliffe, Ryan Adams, Matt Hoffman, Dustin Lang, David Schlegel, and Mr Prabhat. Celeste: Variational inference for a generative model of astronomical images. In *Proceedings of the 32nd International Conference on Machine Learning*, 2015.

[4] Chad M Schafer. A framework for statistical inference in astrophysics. *Annual Review of Statistics and Its Application*, 2:141–162, 2015.

[5] Branimir Sesar, Željko Ivezić, Skyler H Grammer, Dylan P Morgan, Andrew C Becker, Mario Jurić, Nathan De Lee, James Annis, Timothy C Beers, Xiaohui Fan, et al. Light curve templates and galactic distribution of rr lyrae stars from sloan digital sky survey stripe 82. *The Astrophysical Journal*, 708(1):717, 2010.

[6] Branimir Sesar, Željko Ivezić, Robert H Lupton, Mario Jurić, James E Gunn, Gillian R Knapp, Nathan De Lee, J Allyn Smith, Gajus Miknaitis, Huan Lin, et al. Exploring the variable sky with the sloan digital sky survey. *The Astronomical Journal*, 134(6):2236, 2007.